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First Quarterly Report

for the

Design and Development of a Non-Dissipative
Charge Controller
using a
Rotary Transformer

Contract No. NAS5-9204

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1. SUMMARY. - This report is concerned primarily with presenting the calculations for and the design of the electrical and the mechanical portions of the rotary transformer, and to some degree the method of driving it. While preliminary thought was placed on the mechanics of support and rotation in a high vacuum, no specific design was completed during this reporting interval.

Size, configuration, and electrical efficiency were the areas investigated. This required some thought into the electronic DC to AC inverter for driving the transformer. Both square wave and sine wave shapes were evaluated, along with two-transistor and four-transistor drive configurations. The former requires a center tap in the transformer primary.

When a center tap is used, the highest voltage permissible from the solar panel is 40V, due to the low standoff capabilities of the particular transistors chosen. The bridge type inverter using 4 transistors on the other hand can tolerate the full 50V permitted in the contract. Despite the fact that the power current in the 4 transistor configuration must traverse 2 transistors in series, yet the loss figures for the combination of the transformer design and the voltage choice puts the two systems on an equitable footing.

A transformer excitation arrangement was considered where the out-of-phase magnetizing current could flow back and forth freely between the power source and the transformer. This configuration results in high efficiency and low heat generation in the transformer. When transistors are interposed which restrict alternating current flow, the energy stored in the magnetic core and in the air gaps can be recovered only when the power current exceeds the magnetizing current. This requires that there be no significant inductive impedance in the solar cell supply circuits to prevent instantaneous fluctuations in the supply current. A unique design of air gap is discussed which reduces its reluctance to manageable proportions even in the presence of moderate gap lengths.

The case in which the transformer is tuned to operate on sine waves is considered. Stored energy conservation is achieved by placing in the supply line a non-saturated inductance larger than the critical value. This mode of operation is as efficient as square wave operation, and also eliminates spiking during the transistor commutation intervals. Work has not progressed sufficiently to support significant conclusions or recommendations at this time.

## 2. TABLE OF CONTENTS. -

## 3. LIST OF ILLUSTRATIONS. -

4. LIST OF TABLES. -

a. None.

5. INTRODUCTION. - This first quarterly report is to present the findings of the investigations on the contract titled "Design and Development of a Non-Dissipative Charge Controller Using a Rotary Transformer" for the interval between June 17, 1965, and September 17, 1965. During this period, effort has been directed primarily toward evaluating the possible electrical and mechanical designs of the rotary transformer. Circuitry has been considered only where it directly affected the system efficiency in cooperation with the transformer. Several configurations have been analyzed. These include:

1. Center tapped primary using a 2-transistor switch
2. Single winding primary using a 4-transistor switch
3. Sine wave operation.

The need behind the effort of this contract is to provide equipment which will utilize the energy delivered by a solar panel to the best advantage. Because the internal characteristics of the cells and the available power vary over wide limits depending on the instantaneous temperature and insolation, the impedance of the array must be continually probed and the load impedance adjusted to insure maximum power transfer. Other conditions bear on the problem. The battery being charged must not be permitted to overcharge, especially during periods of light loads and high available energy. On the other hand, a low battery must be charged as fast as possible with a limited power to work with. As the battery approaches and reaches the full-charge condition, the charging rate must be dropped to the trickle charge rate to keep it topped off.

The tasks involved in this contract have been broken down into a number of groups to best utilize available personnel. This can be seen by referring to Figure PD-6.

Power coming from the solar panel enters box #1 which contains the low voltage limit cutout, the oscillator, and the power chopper. This is being developed by one group at Matrix. The rotary transformer, box #2, is limited to the mechanical and electrical components and does not include any active devices. This unit is being developed by a second group at Matrix. The post-transformer complex, box #3, contains the remainder of the circuitry including the pulse width modulator, the maximum power detector, the full-charge detector, various current and voltage regulating devices, and the battery.

The work performed during this reporting interval consisted of a detailed design of the electrical and mechanical (except the bearings and support) portions of the rotary transformer. In addition, a study was made of the relative advantages of operating the transformer primary

1. In a 4-transistor bridge chopper
2. In a center-tapped 2-transistor chopper, and
3. In a tuned sine wave 2-transistor class B circuit. In the latter case, the use of larger than critical valued non-saturated chokes in both the supply line to the tuned primary circuit and in the filter after the rectifier of the transformer secondary output will make this mode electrically equivalent to the square wave operation with the advantage that transistor commutation spiking is virtually eliminated, and the stored magnetic energy of the core magnetization is concerned. This should raise the efficiency of the system.

The work contemplated during the next reporting period is the fabrication of one or more configurations of the rotary transformer and the setting up of the electronics for evaluation and refining. This circuitry is shown in Figure PD-8.

## 6. DISCUSSION

6.1 TEST TRANSFORMER. - The first mechanical design excluded the problems of rotation and final support. The magnetic configuration, however, was chosen to permit rotation without perturbing the electrical characteristics. Two standard Ferroxcube ferrite cup cores as per Fig. PD-1 were utilized. One was wound with 9 turns of litz wire (105 strands of #38 enamel wire) and the other with 8 turns. These were then bolted with a nylon bolt to form a nearly closed magnetic path. The winding in one cup was used as the primary and the other as the secondary. The following data were measured or calculated.

6.1.1 <u>Wire Characteristics.</u> -

1) (DC resistance = AC resistance at 10KH) = 0.00630 ohms per foot. $t = 25^{o}C$.

2) Length for 9 turns = 17.7 inches
for 8 turns = 15.7 inches

3) Resistance for 9 turns = $\frac{17.7}{12}(.00630) = .00938$ ohms at $25^{o}C$.

4) Resistance for 8 turns = $\frac{15.7}{12}(.00630) = .00832$ ohms at $25^{o}C$.

5) Resistance of wire at $65^{o}C$ = .00718 ohms per foot.

6) Resistance for 9 turns = $\frac{17.7}{12}(.00718) = .0106$ ohms at $65^{o}C$.

7) Resistance for 8 turns = $\frac{15.7}{12}(.00718) = .00940$ ohms at $65^{o}C$.

Now the primary was wound with 9 turns and the secondary with 8.

6.1.2 <u>Test Parameters.</u> -

8) Output load resistance = 16 ohms

9) Frequency (sinusoidal) = 10,000 hertz

| | | Peak to Peak | RMS |
|---|---|---|---|
| 10) | Input volts | 24.5 | 8.65 |
| 11) | Input amp | 4.4 | 1.56 |
| 12) | Output volts | 21.0 | 7.42 |
| 13) | Output amp | 1.58 | 0.56 |

6.1.3 Calculations. -

14) Output watts = $\underset{(12)}{(7.42 \text{ volts})}\ \underset{(13)}{(0.56 \text{ amp})}$ = 4.15 watts

15) Power factor = $\dfrac{\text{output watts}}{\text{input voltamperes}}$

$$\cos\theta = \frac{\overset{(14)}{4.5 \text{ watts}}}{\underset{(10)}{(8.65 \text{ volts})}\ \underset{(11)}{(1.56 \text{ amps})}} = 0.3074$$

16) Phase angle = $\cos^{-1} .3074 = 72.10$ degrees. This assumes negligible internal losses. The worst actual case (still ignoring iron losses) would include the copper losses at high temperature, say 65°C.

From 6), 7), 11), and 13), we get the

17) Secondary copper losses = (output current)$^2$ (secondary res.)

$P_{cults} = \underset{(13)}{(0.56 \text{ amp})^2}\ \underset{(7)}{(.0094 \text{ ohms})} = 0.0029$ watts at 65°C.

18) Primary copper losses = (input current)$^2$ (primary resistance)

$P_{culpt} = \underset{(11)}{(1.56 \text{ amp})^2}\ \underset{(6)}{(0.0106 \text{ ohms})} = 0.0258$ watts at 65°C.

The actual power involved is,

19) $P_\Sigma$ = Load power + sec. losses + prim. losses

$$P_\Sigma = \underset{(14)}{4.15 \text{ watts}} + \underset{(17)}{0.0029 \text{ watts}} + \underset{(18)}{0.0258 \text{ watts}}$$

$$= 4.18 \text{ watts}$$

The actual power factor is more nearly

20) $$\cos\theta = \frac{\overset{(19)}{41.8 \text{ watts}}}{\underset{(10)}{(8.65 \text{ volts})}\ \underset{(11)}{(1.56 \text{ amps})}} = 0.310$$

and the phase angle is

21) $$\theta = \cos^{-1} \overset{(20)}{0.310}$$

$$= 71.95^{o}$$

The magnetizing current is

22) $$I_m = (\text{Input current}) \sin\theta$$

$$= \overset{(11)}{(1.56 \text{ amp})} \sin \overset{(21)}{\theta} = 1.48 \text{ amperes.}$$

With 9 turns on the primary, the magnetizing ampere turns were

23) $$NI = 9 \text{ turns } \overset{(22)}{(1.48 \text{ amperes})} = 13.32 \text{ ampere-turns.}$$

6.1.4 Efficiency. - Since this was excited with a sinusoidal waveform, the circulating magnetizing power is considered conservative and is found to be

24) Exciting voltamperes = (Input volts) (magnetizing current)

$$EI_{ex} = \underset{}{\overset{(10)}{(8.65 \text{ volts})}}\ \overset{(22)}{(1.48 \text{ amp})} = 12.8 \text{ voltamperes.}$$

This does not represent a power loss. Therefore the efficiency is

25) $$\eta = \frac{\text{output power}}{\text{input power}} = \frac{\overset{(14)}{4.15 \text{ watts}}}{\underset{(19)}{4.18 \text{ watts}}} = 0.992$$

This ignores iron losses. For these calculations, no figure of actual iron losses were available. Suppose, however, they would be equal to the copper losses, the efficiency would have been

$$26)\quad \eta = \frac{\overset{(14)}{4.15\ \text{watts}}}{\underset{(14)}{4.15\ \text{watts}} + 2(\underset{(17)}{.0029} + \underset{(18)}{.0258})\ \text{watts}} = \frac{4.15}{4.21} = 0.987$$

6.2 THE MATHEMATICAL TRANSFORMER MODEL. - The following design has taken into account the practical requirement of mechanical rotation and small bearing stiction. In principle this means that bearings should be small in diameter and lightly loaded. In the space environment, bearings are free from gravitational forces, and there remain only the magnetic moment with the earth's field, the electromagnetic air gap forces, electrostatic forces, maneuvering inertial forces, and forces due to strained secondary leads. Of these, the significant ones are considered to be the electromagnetic airgap forces and the strained wire forces. Inertial forces will be greater, but momentary. Airgap forces can be reduced to negligible proportions by balancing them, as in an arrangement in which all lines of force are normal to the axis of symmetry (radial). Edge fringing effects can be balanced also by having symmetrical shapes at each end of the transformer. Fig. PD-2 illustrates the principle and is the design used for subsequent analysis along with Fig. PD-3. The magnetic circuit is composed of a core 0.750" in diameter ($d_4$) with a 0.285" diameter hole ($d_5$). The net area is

$$27)\quad A_{CO} = \frac{\pi}{4}\left(d_4^2 - d_5^2\right)$$

$$= \frac{\pi}{4}\left[(0.750\ \text{in})^2 - (0.285\ \text{in})^2\right]$$

$$= 0.380\ \text{in}^2\ \frac{(2.54\ \text{cm})^2}{1\ \text{in}^2} = 2.45\ \text{cm}^2$$

The outer diameter is 1.75" diam. ($d_1$). With the outer shell wall thickness of, say, 0.125", the outer diameter of the secondary coil will be 1.500". If half the window height is relegated to the primary winding and half to the secondary, and further if the magnetic circuit is broken by 2 air gaps which are coincident with the outer diameter of the primary (inner) coil, it would be at a diameter of

$$28) \quad \text{Diameter of airgap cylinder} = \overset{(27)}{.750''} + \frac{(1.500'' - \overset{(27)}{0.750''})}{2}$$

$$d_3 = 0.750 \text{ in} + \frac{(1.500 \text{ in} - 0.750 \text{ in})}{2}$$

$$= 1.125 \text{ in} \frac{(2.54 \text{ cm})}{1 \text{ in}} = 2.860 \text{ cm.}$$

For a trial calculation, let the airgap length be

$$29) \quad t_g = 0.004 \text{ in} \frac{(2.54 \text{ cm})}{1 \text{ in}} = 0.1015 \text{ cm}$$

Also, let the area be equal to the area of the core (see note at end of this section)

$$30) \quad A_g = \overset{(27)}{0.380} \text{ in}^2 \frac{(2.54 \text{ cm})^2}{1 \text{ in.}^2} = 2.45 \text{ cm}^2$$

Since this is at 1.125" diameter, the axial length (thickness of the webb) will be

$$31) \quad A_g = \pi d_3 l_2 = \overset{(27)}{.380} \text{ in}^2 \frac{(2.54 \text{ cm})^2}{1 \text{ in}^2} = 2.45 \text{ cm}^2$$

or $$l_2 = \frac{.380 \text{ in}^2}{1.125 \, \pi \text{ in}} = .1075 \text{ in} \frac{(2.54 \text{ cm})}{1 \text{ in}} = 0.236 \text{ cm.}$$

The shell thickness was set arbitrarily at 0.125 in for mechanical reasons. Its area will be larger than that of the core. It will be

$$32) \quad A_{sh} = \frac{\pi}{4} \left[ (1.75 \text{ in})^2 - \underset{(28)}{(1.50 \text{ in})^2} \right] = (3.063 - 2.250) \frac{\pi}{4}$$

$$A_{sh} = 0.640 \text{ in}^2 \frac{(2.54 \text{ cm})^2}{1 \text{ in}^2} = 3.99 \text{ cm}^2$$

From data furnished by the ferrite supplier (Biblio #1) the operating point was tentatively chosen, at which the following facts hold

33) $\varphi$ = flux density = gauss = 1345 = arbitrary (from curves).

34) Material loss ("residual") = $2.8(10)^{-6} \frac{\text{watts}}{\text{Hcm}^3} = K\varphi 1345$

(1)

For an operating frequency of 10,000 H it is

35) $FK_{\varphi}1345 = 2.8\ (10)^{-2}$ watts/cm$^3$

The value for loss above is almost constant in the vicinity of 10KH, varying directly as the square of the flux density.

36) $P_{\varphi 1} = 2.8\ (10)^{-6}\ \left(\frac{\varphi}{1345}\right)^2 \frac{\text{watt-sec.}}{\text{H cm}^3}$ (from curves)

37) Initial permeability $\mu_o$ = 1200

Let the coil length be

38) $l_1 = 1.5 \text{ in } \left(\frac{2.54 \text{ cm}}{1 \text{ in}}\right) = 3.81 \text{ cm}$

The effective magnetic length of the shell or core is equal to the coil length plus the thickness of one end webb

39) core mag length = $(\overset{(38)}{1.500} + \overset{(31)}{.107})$ in $\approx 1.61$ in $\left(\frac{2.54 \text{ cm}}{1 \text{ in}}\right)$

= 4.09 cm

If the outside diameter of the secondary coil is 1.500 in., and the core diameter is 0.75 in., the magnetic effective length of each webb is

40) $l_{mw} = \frac{\overset{(38)}{1.500 \text{ in}} - \overset{(27)}{0.750 \text{ in}}}{2} + (.063 \text{ in} = 1/2 \text{ shell thickness})$

$+ (0.152 \text{ in} = 0.4 \text{ core radius}) = 0.590 \text{ in } \left(\frac{2.54 \text{ cm}}{1 \text{ in}}\right)$

= 150 cm

The total magnetic length excluding the shell is

$$41)\quad \Sigma_{1m} = \overset{(39)}{1.61 \text{ in}} + 2\ \overset{(40)}{(0.590 \text{ in})}$$

$$= 2.79 \text{ in } \frac{(2.54 \text{ cm})}{1 \text{ in}} = 7.10 \text{ cm}$$

To evaluate the effect of magnetizing losses with different areas of air gaps, the ampere turns required for the circuit will be calculated. Ampere turns for a flux density of 1345 gauss for the core and webbs are developed first. Length units are centimeters.

$$42)\quad \frac{NIcow}{lmcm}\ \frac{(4\pi)}{10}\mu_o = \varphi = \overset{(33)}{1345 \text{ gauss}} = 1200\ \frac{(4\pi)}{10}\ \frac{NIcow}{lmcm}$$

$$43)\quad (NI)_{cow}\ \frac{\overset{(33)}{1345}(10)lm}{4\pi\ \mu_o} = \frac{3360}{\pi}\ \frac{\overset{(41)}{(7.10)}}{\underset{(37)}{1200}} = 6.32 \text{ temperature}$$

The magnetizing force for the shell is

$$44)\quad NI_{sh} = \overset{(43)}{6.32}\ \frac{\overset{(27)}{(2.45)}}{\underset{(32)}{3.99}}\ \frac{\overset{(39)}{(4.09)}}{\underset{(41)}{7.10}} = 2.24 \text{ ampere turns}$$

where

| | |
|---|---|
| 6.32 = NI for core plus 2 webbs | (43) |
| 2.45 = area of core and webbs ($cm^2$) | (27) |
| 3.99 = area of the shell ($cm^2$) | (32) |
| 4.09 = length of shell (cm) | (39) |
| 7.10 = length of remainder of magnetic circuit (cm) | (41) |

Let the airgap length be

$$45)\quad t_g = 0.004 \text{ in } \frac{(2.54 \text{ cm})}{1 \text{ in}} = 0.01015 \text{ cm}$$

With an area of $A_g$ of 2.45 $cm^2$, (27) the airgap ratio without fringing effects is

$$46) \quad \frac{t_g}{A_g} = \frac{\overset{(45)}{.01015\ \text{cm}}}{\underset{(27)}{2.45\ \text{cm}^2}} = \frac{.00429}{\text{cm}}$$

So the magnetizing force is

$$47) \quad NI_g = \overset{(33)}{(1345\ \text{gauss})}\ \frac{10}{4\pi}\ \frac{\overset{(45)}{.01015}}{\underset{(27)}{2.45}} \quad \text{(2 gaps in series)}$$

$$NI_g = 4.42\ (2) = 8.84\ \text{ampere turns}$$

Total magnetizing forces in ampere-turns is

| | | | |
|---|---|---|---|
| 48) core and webbs | = 6.32) | | (43) |
| shell | = 2.24) | 8.56 | (44) |
| airgaps | = 8.84 | 8.84 | (47) |
| | 17.40 | 17.40 ampere turns | |

The total flux threading the core is

49) Total flux = flux density X core area

$$\Sigma\varphi_{co} = A_{co}\ \varphi_{co} = \overset{(33)}{1345\ \text{gauss}}\ \overset{(27)}{(2.45\ \text{cm}^2)} = 3295\ \text{maxwells}$$

6.2.1 Square Wave Excitation Mode. - The volts per turn which this can support at 10KH is

$$50) \quad \frac{\text{Volts}}{\text{Turns}} = \frac{E}{N_p} = \frac{2\ \text{frequency X}\ \Delta\ \text{flux}}{10^8}$$

$$= \frac{2(10,000)\ \overset{(35)}{(3295)}\ \text{H maxwells}}{10^8}$$

$$= 0.659\ \text{volts peak/turn}$$

The number of turns required to support a battery voltage of 50 volts is

$$51)\quad N_p = \underset{(50)}{\frac{50}{.659}} = 76 \text{ turns}$$

The litz wire tentatively chosen is made up of 105 number 38 wire, polyurethane insulated, double nylon-wrapped. It winds with about 16 turns per linear inch. Three layers each with 24 turns could be tried. The coil length is 1.5", so the number of turns per layer are

$$52)\quad \frac{N_p}{\text{layer}} = \frac{1.500 \text{ in}}{.063 \text{ in}} = \frac{24 \text{ turns}}{\text{layer}}$$

For three layers

$$53)\quad N_p = \overset{(52)}{3(24)} = 72 \text{ layers}$$

This is sufficiently close to the 76 required in equation (51). With 72 turns, the peak magnetizing current is

$$54)\quad I_{pm} = \frac{NT}{N}_{pm} = \frac{\overset{(48)}{17.40}}{\underset{(53)}{72}} = .242\ A_p$$

All the energy stored in air gaps is virtually recovered, except for losses in transistors and diodes. This amounts to that portion of the required ampere turns to magnetize the airgap to the total or

$$55)\quad \frac{\text{airgap magnetizing force}}{\text{total magnetizing force}} = \frac{\overset{(47)}{8.84}}{\underset{(48)}{17.40}} = .508$$

To account for residual losses here, estimate the percentage air gap energy recoverable to be 75%, then the real air gap losses would be

$$56)\quad P_g = \text{total excitation power} \left(\frac{\text{airgap}}{\text{total}} \text{ magnetizing power}\right)$$

$$(1 - \text{airgap efficiency})$$

$$P_g = \text{watts} = \frac{1}{2}\underset{(51)}{(50 \text{ volts})}\ \underset{(54)}{(.242 \text{ amp})}\ \underset{(55)}{(0.508)}\ (1-.75) =$$

$$= .770 \text{ watts}$$

From magnetizing vs induction (B-H) curves supplied by the manufacturer, the residual induction after the magnetizing force is removed falls to about 85% of the peak value for typical non-saturating levels.

The ferrite excitation losses similarly are

$$57)\quad P_{fexl} = \frac{1}{2}\underset{(51)}{(50 \text{ volts})}\ \underset{(54)}{(.242 \text{ amp})}\ \left(\frac{\overset{(48)}{8.56 = \text{ferrite NI}}}{\underset{(48)}{17.40 = \text{total NI}}}\right)$$

$$(.85 = K_{\varphi l})$$

$$= 2.53 \text{ watts}$$

The total active magnetizing losses are

$$58)\quad P_{\Sigma ml} = \underset{(56)}{0.770 \text{ watts}} + \underset{(57)}{2.53 \text{ watts}} = 3.30 \text{ watts}$$

To this there must be added a so-called "residual" loss specified by the ferrite supplier as equal to

$$59)\quad P_{residual} = \overset{(34)}{2.8\ (10)^6}\ \frac{\text{watts}}{\text{Hcm}^3} = K\varphi 1345$$

The volume of that portion of the magnetic circuit operating at 1345 gauss is

$$V_{1345} = V_{co} + V_w = \underset{}{\overset{(27)\ (39)}{10.00 \text{ cm}^3}} + \overset{(30)\ (40)}{7.35 \text{ cm}^3} = 17.35 \text{ cm}^3$$

The core loss at $H = (10)^4$

$$60)\quad P_{cow}\ \ \overset{(34)}{2.8\ (10)^{-6}}\ \ \overset{(59)}{17.35}\ (H = 10^4) = 0.49 \text{ watts}$$

The shell operates at a lower density than the core because its cross sectional area is larger. The flux density is

$$61)\quad \varphi_{sh} = 1345 \overset{(33)}{} \frac{\text{core area}}{\text{shell area}} \text{ gauss}$$

$$\varphi_{sh} = 1345 \; \frac{\overset{(27)}{2.45}}{\underset{(32)}{3.99}} \text{ gauss} = 825 \text{ gauss}$$

The residual losses are proportional to the square of the peak induction, or

$$62)\quad \text{Loss constant of shell} = K_{\varphi 825} = \overset{(34)}{2.8\,(10)^{-6}}$$

$$\frac{\overset{(61)}{(\varphi sh = 825)^2}}{\underset{(33)}{1345^2}} \quad \frac{\text{watts}}{\text{H cm}^3}$$

$$K_{\varphi 825} = 1.06\,(10)^{-6} \frac{\text{watts}}{\text{H cm}^3}$$

Shell losses then are

$$63)\quad P_{shl} = \overset{(62)}{1.06\,(10)^{-6}} \; \overset{(35)}{(10)^4} \; \overset{(32X39)}{16.32} \text{ watts}$$

$$= 0.172 \text{ watts}$$

Total ferrite losses are

$$64)\quad P_{fl}\,(50V) = \sum \text{partial losses} = \overset{(60)}{.49} + \overset{(63)}{.172} = .662 \text{ watts}$$

Copper losses associated with (58) will now be determined. Assume the exciting current waveform to be triangular, the rms value is

$$65)\quad I_{exrms} = I_{pm} \frac{1}{3}\sqrt{3}$$

This times the primary resistance will give the accompanying copper loss.

The primary wire length is

66) $R_p$ = average length of turn X no. turns X resistance

$$R_p = \frac{\pi}{12}\left(\frac{\overset{(27)}{.750} + \overset{(28)}{1.125}}{2}\right) 72 \;(\overset{(5)}{.00718}) \text{ ohms}$$

$$= 0.127 \text{ ohms}$$

The excitation copper loss is

67) $$P_{excul} = I^2_{exrms} R_p = \overset{(54)}{(.242)^2}\,\overset{(65)}{(.577)^2}\;\overset{(66)}{0.127} = .0024 \text{ watts}$$

Non-recoverable excitation losses are

68) $$P_{exl} = \overset{(56)}{0.770} + \overset{(57)}{2.53} + \overset{(60)}{0.490} + \overset{(63)}{0.172} + \overset{(61)}{0.002}$$

$$= 3.71 \text{ watts}$$

This represents the standby losses. Total full load losses will be based on a 100 watt load at 50 volts. The load current then is

69) $$I_{orms} = \frac{\text{watts}}{\text{volts}} = \frac{100}{50} = 2 \text{ amperes}$$

With this added to the excitation current of 0.242 amperes, the rms value can be approximated by

70) $$I_{exrms} \approx \text{amp} + \frac{1}{2}\overset{(54)}{(0.242)} \text{ amp} = 2.121 \text{ amperes}$$

Primary copper losses are

71) $$P_{culpt} = \overset{(70)}{(2.121)^2}\,\overset{(66)}{(0.127)} = 0.572 \text{ watts}$$

Without at this time setting the transformer ratio, the secondary losses will be higher than the primary by the ratio of resistance

$$72)\quad R_s = R_p \frac{\overset{(28)}{1.5 + 1.125}}{\underset{(28)}{0.75 + 1.125}} = \frac{\text{average secondary diameter}}{\text{average primary diameter}}$$

$$= \overset{(66)}{.127}\ \frac{(2.625)}{1.875} = .178 \text{ ohms}$$

The secondary losses then would be

$$73)\quad P_{cults} = I_o^2 R_s = \overset{(69)}{(2)^2}\ \overset{(72)}{.178} = .712 \text{ watts}$$

Total losses would then be

$$74)\quad P_{\Sigma 1} = \overset{(68)}{3.71} + \overset{(71)}{.572} + \overset{(73)}{.712} = 5.054 \text{ watts}$$

The power inversion efficiency is

$$75)\quad \eta_i = \frac{\text{output power}}{\text{input power}} = \frac{\overset{(69)}{100} - \overset{(74)}{5.054}}{\underset{(69)}{100}} \approx .95$$

Equation 75) includes losses which are not dissipated within the transformer, and are properly associated with the total immediate conversion process. For instance, the power for the excitation current is derived from the supply volts and is considered largely lost. Outside of the actual copper and iron losses, this energy is spent in diodes and transistors.

76) Ferrite losses (from 64) = .602 watts

77) Copper losses (from 71 and 73) = 1.28 watts

$$78)\quad \eta_\Sigma = \frac{\overset{(69)}{100} - (\overset{(76)}{.602} + \overset{(77)}{1.27})}{\underset{(69)}{100}} \approx 0.98$$

6.2.3 Circuit Considerations. - The choice of the basic operatting voltage for the solar panel configuration depends primarily upon the availability of suitable transistors which can perform the necessary conversion and control functions. For 100 watt operation and with a stipulated 50V as the highest permissible choice, the current would be of the order of 2 amperes. Circuit efficiency is to be considered first for the first DC to AC inverter which permits the power to be transmitted through the rotary transformer. For the order of magnitude of current indicated above, the power lost in the switching transistors from its saturated collector to emitter voltage is sizeable, and therefore should be kept to a minimum. This fact considered alone would indicate a two-transistor inverter using a center-tapped transformer primary. However, this requires one-half of the primary winding to be always idle, which results in a larger and lossier unit. It also imposes serious voltage burdens on the transistors, more than doubling their standoff requirements. It is true that commutating spike voltages can exceed the continuous maximum rating without detriment, if they are short enough, but it is not deemed expedient to build in this condition as a steady operating requirement. In looking over the field for a suitable transistor, a trial choice is the 2N2879, rated at 5 amperes, and a standoff voltage of 100. The current rating is more than adequate, but for a 50V supply, there is no margin for 2 x 50V + spikes.

79) $$2(E_i = 50) + (20 - \text{spikes})$$

$$> (100V = 2N2879 \text{ standoff voltage})$$

Let us say that a voltage of 40 be chosen so that there would be a 20V spike margin, which can be safely observed. The current required to deliver 100 watts from the panel would be

80) $$I = \text{amperes} = \frac{\text{watts}}{\text{volts}} = \frac{100}{40} = 2.5 \text{ amperes}$$

From the operating curves for the 2N2879 transistor at $100^{o}C$ the collector-to-emitter saturation voltage for 2.5 amp collector current is

81) $E_{sace} = 0.33$ volts

The collector loss per series transistor is

82) $$P_{cl} = E_c I_c = \overset{(81)}{(0.33)}\ \overset{(80)}{(2.5)} = 0.83 \text{ watts}$$

To drive this transistor requires at least

83) $$I_{bs} = \frac{1}{10} I_c = \frac{2.5}{10} = .25 \text{ amperes}$$

To take care of temperature variations and perturbations of power current, a margin of say 50% is required to insure saturation at all times, so

84) $$I_{bsace} = .25 \times \frac{150\ \%}{100\ \%} = .375 \text{ amperes}$$

The base-to-emitter voltage is

85) $E_{be} = 1$ volt

from published curves. The base loss then is

86) $$P_{bl} = E_{be} I_b = \overset{(85)}{(1)}\ \overset{(84)}{(.375)} = .375 \text{ watts}$$

The total transistor dissipation then, not counting spike or commutating losses is the sum of 82) and 86) or

87) $$P_{\Sigma Q1} = \overset{(82)}{0.83} + \overset{(86)}{0.375} = 1.21 \text{ watts}$$

To drive the base and stabilize the current, a limiting resistor is required. Set a value for it arbitrarily and let it be

88) $R_{bextr} = 1$ ohm

So, the voltage drop across it for a current of .375 amperes is

89) $$E_{bextr} = E_{be} I_b = \overset{(85)}{(1)}\ \overset{(84)}{(.375)} = .375 \text{ volts}$$

The driving transformer winding voltage, therefore, must be

90) $E_{bex}$ = transistor base voltage + resistor voltage.

$$E_{bex} = \overset{(85)}{1} + \overset{(89)}{.375} = 1.375 \text{ volts}$$

The total driving power per transistor pair is

91) $$P_{\Sigma Qd1} = (E_{bex})\,(I_b) = \overset{(90)}{(1.375)}\;\overset{(84)}{(.375)} = 0.515 \text{ watts}$$

To refer this to primary power consumption, consider it to be generated by an oscillator with an efficiency of 85%, so

92) $$\text{Primary power drain} = \frac{\text{output power}}{\text{efficiency}} = \frac{\overset{(91)}{0.515}}{0.80}$$

$$= 0.645 \text{ watts}$$

Transistor losses for a 2Q configuration (2 power transistors using a center-tapped transformer at $E_i$ = 40V) are

93) $$P_{\Sigma Q1} = \overset{(92)}{0.645} + \overset{(82)}{0.83} = 1.48 \text{ watts}$$

In a bridge circuit the current traverses two series transistors so the Q losses are doubled and for the same supply of 40V would be

94) $$2P_{\Sigma Q1(40V)} \;\; 2\,(\overset{(93)}{1.48} \text{ watts}) = 2.96 \text{ watts}$$

However, for a bridge rectifier the voltage could be higher so the current drain from the solar panel would be 2 amperes instead of 2.5 amperes and the new losses in the bridge inverter would approximate

95) $$2P_{\Sigma Q(50V)} \approx \left(0.8 = \frac{2}{2.5}\right) \overset{(94)}{2.96} = 2.3 \text{ watts}$$

As mentioned above, this is the steady state inter-switching loss estimate and does not include commutating or spiking losses.

Transformer changes required to accommodate the two-transistor inverter result in a heavier and less efficient design. In the first place the primary turns have to be doubled, since only half are used in any half cycle. Secondly, the supply voltage must be lowered to prevent over-voltaging the transistors. This affects the number of turns in the primary and secondary and also the length of the magnetic circuit. Thus its size and conversion efficiency are modified. These changes are calculated below:

For a supply of 40V, the number of primary turns required to support a square wave at 10,000 hertz are

$$96)\quad N = \frac{\overset{(80)}{40}}{\underset{(50)}{.659}} \approx 60 \text{ turns}$$

For 3 layers, this requires 20 turns/layer and the coil length is

$$97)\quad B = \overset{(52)}{(.063)}\ (1 + 20.3) = 1.34''$$

This extra turn space allows for the stacking factor. For a center tapped winding of 60 turns per side the core length must be twice this or

$$98)\quad 2B = 2\overset{(97)}{(1.34 \text{ in})} = 2.68 \text{ in.}$$

The new magnetizing forces are

$$99)\quad NI_{sh} = \overset{(44)}{2.21}\ \frac{\overset{(98)}{(2.68)}}{\underset{(39)}{1.60}} = 3.70 \text{ ampere-turns}$$

and

$$100)\quad NI_{cow} = \overset{(43)}{5.58}\ \left( \frac{\overset{(98)\,(40)}{3.556}}{\underset{(41)}{2.473}} \right) = 8.02 \text{ ampere-turns}$$

Total NI is

$$101)\quad NI_{\Sigma} = \overset{(47)}{8.84} + \overset{(99)}{3.70} + \overset{(100)}{8.02} = 20.56 \text{ ampere-turns}$$

With 60 primary turns, the peak exciting current is

$$102)\quad I_{pex} = \frac{\overset{(101)}{20.56}}{\underset{(96)}{60}} = 0.343 \text{ amp.}$$

The excitation losses with a 40V supply are

$$103)\quad P_{\Sigma ex(40V)} = \overset{(56)}{0.770} + \frac{\overset{(102)}{0.343}}{2}\ \overset{(80)}{(40)}\ \overset{(57)}{(.85)} = 6.60 \text{ watts}$$

$$104)\quad \frac{N(40V)}{N(50V)} = \frac{\overset{(96)}{60}}{\underset{(53)}{72}} = .835$$

$$105)\quad R_p = \overset{(66)}{0.127}\ \overset{(104)}{(.835)} = 0.106 \text{ ohms}$$

$$106)\quad R_s = \overset{(72)}{.178}\ \overset{(104)}{(.835)} = 0.148 \text{ ohms}$$

$$107)\quad I_{prms} \approx \overset{(80)}{2.5} + 1/2\ \overset{(102)}{0.343} = 2.671 \text{ amperes}$$

$$108)\quad I_{srms} = \overset{(80)}{2.5} = 2.5 \text{ amperes}$$

$$109)\quad P_{pcul} = I^2_{prms} R_p = \overset{(107)}{(2.67)^2}\ \overset{(105)}{(0.106)} = .755 \text{ watts}$$

$$110)\quad P_{scul} = I^2_{srms} R_s = \overset{(108)}{(2.5)^2}\ \overset{(106)}{(0.148)} = 0.925 \text{ watts}$$

$$111)\quad P_{\Sigma cul(40V)} = \overset{(109)}{0.755 \text{ watts}} + \overset{(110)}{0.925 \text{ watts}} = 1.680 \text{ watts}$$

The copper losses for a 50V supply are

$$112)\quad P_{\Sigma cul(50V)} = \underset{(71)}{0.572\text{ watts}} + \underset{(73)}{0.712\text{ watts}} = 1.28\text{ watts}$$

The increased copper loss at 40V is

$$113)\quad P_{\Sigma cul(40V)} - P_{\Sigma cul(50V)} = \overset{(111)}{1.68\text{ watts}} - \overset{(112)}{1.28\text{ watts}}$$

$$= 0.40\text{ watts}$$

The increase of transformer excitation losses at 40V is

$$114)\quad P_{exl(40V)} - P_{exl(50V)} = \overset{(103)}{4.81\text{ watts}} - \overset{(57)}{2.28\text{ watts}}$$

$$= 2.53\text{ watts}$$

The airgap losses are the same for each voltage.

$$115)\quad P_{gexl(40V)} - P_{gexl(50V)} = 0$$

Ferrite losses at 40V supply are proportional to its volume for the same operating peak magnetic flux.

$$116)\quad P_{\Sigma fl(40V)} = P_{cow(50V)} \left(\frac{V_{cow(40V)}}{V_{cow(50V)}}\right) + P_{sh(50V)} \left(\frac{V_{sh(40V)}}{V_{sh(50V)}}\right)$$

$$= \overset{\substack{(27)(31)\\(36)(38)}}{0.460} \left( \frac{\overset{(98)(27)(31)}{23.8\text{cm}^3}}{\underset{(27)(38)(31)}{16.45\text{ cm}^3}} \right)\text{ watts} +$$

$$+ \overset{\substack{(32)\\(38)(62)}}{0.161} \left( \frac{\overset{(98)\ (32)}{27.2\text{ cm}^3}}{\underset{(38)\ (32)}{15.20\text{ cm}^3}} \right)\text{ watts}$$

$= 0.66 \text{ watts} + 0.44 \text{ watts}$

$= 1.10 \text{ watts}$

The losses of inversion at 40V and 2 transistors

$$117) \quad P_{\Sigma 1(40V)} = \overset{(103)}{6.60 \text{ watts}} + \overset{(111)}{1.68 \text{ watts}} + \overset{(93)}{1.48 \text{ watts}} + \overset{(116)}{1.10 \text{ watts}}$$

$$= 10.86 \text{ watts}$$

To obtain the inversion losses for the 50V bridge chopper configuration, it is necessary as before to collect the partial losses as

Transformer magnetizing losses
Ferrite losses
Copper losses
Transistor losses

At 50V, the load current for 100 watts is 2 amp (69). The transformer magnetizing losses are

$$118) \quad P_{\Sigma m1} = 3.71 \text{ watts} \quad (68)$$

$$119) \quad P_{\Sigma f1(50V)} = 0.662 \text{ watts} \quad (64)$$

$$120) \quad P_{\Sigma cu1(50V)} = 5.05 \text{ watts} \quad (74)$$

$$121) \quad \frac{1}{2} P_{\Sigma Q1(50V)} = (E_{sace} = .31V)^2 (I_i = 2.12) + (E_{bex} = 1.30)(I_b = 0.3)\left(\frac{1}{.8}\right)$$

$$= 0.657 + 0.49 = 1.147 \text{ watts}$$

$$122) \quad P_{\Sigma Q1} = 2(1.147) = 2.294 \text{ watts} \quad (95)$$

So,

$$123)\quad P_{\Sigma 1(50V)} = \overset{(118)}{3.71\text{ watts}} + \overset{(64)(116)}{0.66\text{ watts}} + \overset{(74)}{5.05\text{ watts}} + \overset{(95)}{2.29\text{ watts}}$$

$$= 11.71\text{ watts}$$

Comparing this loss with that of the 2 transistor inverter, they are sufficiently close to be insignificant, since commutating and spiking losses are not considered, and the rather large portion attributable to the non-recoverable magnetizing losses are admittedly pessimistic. The comparison is

| Chopper | $\Sigma 1$ | $E_p$ |
|---|---|---|
| 4Q | .883 | 50 volts |
| 2Q | .894 | 40 volts |

The closeness of these figures indicates the necessity of setting up parallel trials which can be done easily on the preliminary circuit breadboard.

Figures PD-2 and PD-3 show a magnetic circuit slightly different from what is discussed. The airgap area is roughly 7 times the area of the one discussed in equation (31). The magnetizing force required to drive 2 of these gaps is listed in equation (47). This is roughly half of that required for the entire magnetic circuit for the bridge type inverter. The following discussion assumed the stored energy of the airgap to be largely recoverable as reflected in equation (56). If it is not, then the airgap losses will be 4 times the value of 0.770 watts, or

$$124)\quad 4P_g = \overset{(56)}{4(0.770\text{ watts})}$$

$$= 2.980\text{ watts}$$

This would increase the losses in equation (123) from 11.71 watts to

$$125)\quad P_{\Sigma 1\ (50V)} = \overset{(123)}{11.71\text{ watts}} + (3P_g = 2.31)\text{ watts}$$

$$= 14.02\text{ watts}$$

and the efficiency would drop to

$$126) \qquad \Sigma 1(50V) \overset{(125)}{=} .86$$

With the large airgap area, the magnetizing force would drop from 8.84 (47) ampere turns to 1.26 ampere turns. The resulting efficiency would be

$$127) \qquad \Sigma 1(50V) = .886$$

Figure PD-4A is a typical representation of a sinusoidal voltage wave (1) with the current, which includes power and magnetizing components (2). In Figure PD-4B, the current is broken into real and imaginary components, with the power current (long dashed curve) in phase with the applied voltage (2) and the magnetizing current (short dashed curve) in quadrature (3).

For the square wave case, Figure PD-4C illustrates a possible situation. The circuit is shown in Figure PD-5. This is a rudimentary schematic which does not include any of the refinements of the power matching networks. The voltage $E_2$ supplies the transistors $Q_3$ and $Q_4$ which drive the rotary transformer T-2. $E_1$ supplies the saturating oscillator-exciter transistors $Q_1$ and $Q_2$ which cooperate with transformer T-1. This furnishes square waves in the 10KH region.

Referring again to Figure PD-4C, the solid line (1) represents the voltage across the whole primary of T-2. The dotted line (2) shows the typical power current. The dashed line (3) shows an ideal core magnetizing current wave shape. An ideal core is one which has a constant permeability and zero hysteresis. Since the impressed wave form is square, the magnetizing current wave form is triangular, and in lagging time quadrature to the voltage. Thus at the beginning of each half cycle, the excitation current and the power current are in opposition. The algebraic sum of these must be positive, that is, the power current must always be larger than the excitation current if the polarity on $Q_3$ or $Q_4$ is to be such as to be conducting. During this time, energy which has been stored in the magnetic core is being extracted, and so long as the above relationship exists, this is largely recovered and transferred to the load. In this respect, the circulating magnetizing power is not being completely lost.

The square wave case and the sine wave case are similar. The two cases differ, however, to the extent that in the sine wave case, the magnetizing current can be the larger of the two, since magnetizing power is conservative and simply surges back and forth between the power source and the transformer. The square wave case, on the other hand, differs in that it can be considered only a quasi-conservative system. In each half cycle, all the stored energy in the core must be supplied by the battery, and instead of this energy circulating between the core and the power source, it is dumped each half cycle into the load. The power efficiency is roughly the same, because what energy the core delivers to the load, the source does not have to supply. The only restriction is that power current be larger than the instantaneous magnetizing current. If the reverse is true, then at the beginning of each half period, the current is completely interrupted in $Q_3$ and $Q_4$, and at this point any remaining energy in the core is dissipated as shock-excited damped waves in the self-inductance of the transformer and stray circuit capacitance.

Again in the practical case, the ferrite does not return all the the energy which is stored in it. The effect is to add to the losses of the system by heating the core. The effect on the current is shown in Figure PD-4D. The dashed line (2) shows the magnetizing and load currents of PD-4C added. The dotted line (3) shows the effect of hysteresis. The magnetizing current drops more rapidly to zero in the first half of each half period, thus not returning all the stored energy. The energy required to magnetize the core in the opposite sense then comes from the power source. The net loss is measured by the area between the curves (2) and (3). These wave forms would exist with the circuit of Figure PD-5 with the switch $S_1$ closed so that current drawn from the source can pulsate without changing the applied voltage to the power amplifiers $Q_3$ and $Q_4$.

If the values of the primary inductance of T-2 and the capacitance C1 are chosen to be in resonance at the operating frequency, and further to have sufficiently low individual reactances to permit 10 or more times the power current as the circulating tank current, then the system will operate with essentially sine waves on the transformer with S closed, even with square waves impressed on the bases of $Q_3$ and $Q_4$. Figure PD-7 shows the various wave forms involved with this mode of operation. Figure PD-7A is the AV wave form across capacitor C1 (Figure PD-5) and the terminals of transformer T-2. In Figure PD-7B, the solid line shows the instantaneous voltage across the collector-emitter terminals of the transistor $Q_3$, and similarly the dashed line shows the voltage across $Q_4$. This means that the voltage at the center tap of T-2 will follow the well known full wave rectified and unfiltered form consisting sequentially of the dashed line above the base line for one-half cycle, then the solid line for the next half cycle, then the dashed line again, etc. This wave form is also across L-1 working about $E_i$ as the supply volts. In this case L-1 should have high reactance at all significant harmonics of the operating frequency. When the voltage is rectified from the secondary, the choke L-2 (Figure PD-5) is larger than the critical value will permit the same rectification efficiency for sine wave operation as with square wave. Figure PD-7C shows the base drive voltage for transistor $Q_3$.

7. <u>NEW TECHNOLOGY.</u> - During this reporting interval, there were no technologies developed which would fall under this category.

8. PROGRAM FOR NEXT REPORTING INTERVAL. - During the reporting period from September 17, 1965, through December 17, 1965, two parallel avenues will be pursued. The first will be a complete laboratory breadboard setup of the electronics of the Non-Dissipative Charge Controller to determine the dynamic stability constants of the system, which will include the comparison of true maximum power detection with the alternative of detecting the maximum current as a means of controlling the current drawn from the solar panels. This will take into account the possibility that at some future date a new panel might be utilized which would have different characteristics from what is presently anticipated. This setup will also permit the evaluation of different methods of driving the primary of the rotary transformer, with respect to their particular weight and power economies.

Among the modes to be checked are

1. Two-transistor inverter using a center-tapped transformer primary

2. Four-transistor inverter using a non-center-tapped transformer primary

3. Square wave versus sine wave operation of the rotary transformer

4. Means of recovering stored airgap energy.

The second line of activity has to do with the electrical and mechanical design of the rotary transformer itself. As suggested in the main text, one method of reducing excitation losses is to reduce the magnetic reluctance of the airgap. This is to be accomplished by making the gap area large compared to its length. Two typical designs are shown in figures PD-2 and PD-3.

9. <u>CONCLUSIONS AND RECOMMENDATIONS.</u> - The program has not advanced to the point where significant conclusions or recommendations can be made.

# 10. BIBLIOGRAPHY. -

10.1 Preliminary unpublished data from Stackpole Carbon Co., St. Marys, Pennsylvania, on CERMAG 24-B.

10.2 Specifications sheet on HSP transistor #2N2877 and 2N2879, Honeywell Semiconductor Products, Riviera Beach, Florida.

## 11. GLOSSARY

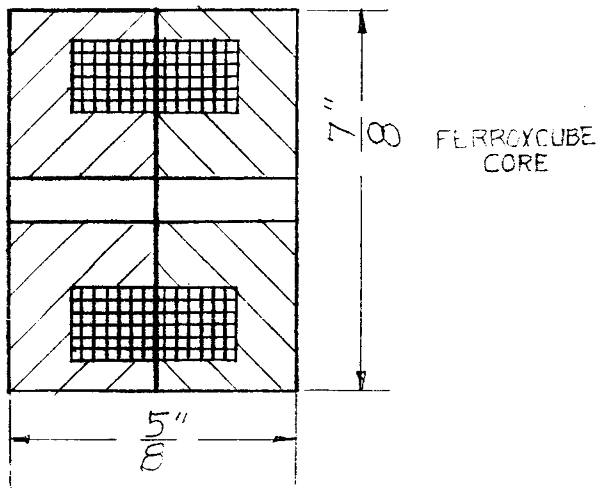
| | |
|---|---|
| $A_{co}$ | Cross sectional area of the core |
| $A_g$ | Area of the air gap |
| $A_{sh}$ | Cross sectional area of the shell |
| AV | Alternating voltage |
| B | Length of transformer winding |
| B | See "Class B" |
| C | Capacitor |
| C | Centrigrade |
| Class B | Operating mode of two transistors in push-pull connection in which only one transistor is conducting at a time, and for 180 electrical degrees. |
| $\cos\theta$ | Power factor |
| d | Diameter |
| E | Volts |
| $E_{be}$ | Transistor base-to-emitter volts |
| $E_{bex}$ | Transistor base-emitter plus base external resistor volts |
| $E_{bl}$ | Transistor base loss |
| $E_{ce}$ | Volts between the collector and emitter of a transistor |
| $E_i$ | Supply volts |
| $E_{sace}$ | Transistor saturated collector-to-emitter volts |
| F | Operating frequency which is 10,000 hertz |

| | |
|---|---|
| H | Hertz |
| $\eta$ | Efficiency |
| $\eta_i$ | Inversion efficiency |
| $\eta_\Sigma$ | Overall efficiency |
| $I_b$ | Transistor base current |
| $I_{bs}$ | Base current to saturate collector-emitter voltage |
| $I_{bsace}$ | Transistor base current to insure collector-to-emitter voltage with 50% margin. |
| $I_{exrms}$ | Exciting current in root mean square amperes. |
| $I_g$ | Used with N as $NI_g$ to represent magnetizing force in the air gap. |
| $I_{orms}$ | Transformer output root-mean-square current |
| $I_{pex}$ | Peak excitation current |
| $I_{pm}$ | Peak magnetizing current |
| $K_{\varphi 825}$ | Ferrite loss constant at a flux density of 825 Gauss in watt-sec per $Hcm^3$ |
| $K_{\varphi 1345}$ | Ferrite loss constant at a peak flux density of 1345 Gauss in watt-sec per $Hcm^3$ |
| L | Inductance |
| l | Length |
| lmcm | Magnetic length in centimeters |
| lmw | Magnetic effective length of the webb |
| N | Number of turns |

| | |
|---|---|
| $N_{(40V)}$ | Primary turns when operating at 40V square wave at 10,000 Hertz |
| $N_{(50V)}$ | Primary turns when operating at 50V square wave at 10,000 Hertz |
| $N_p$ | Number of primary turns |
| $NI$ | Magnetizing force |
| $NI_{cow}$ | Magnetizing force for the core and webbs of the transformer |
| $NI_g$ | Magnetizing force to excite the air gaps |
| $NI_{sh}$ | Magnetizing force in the transformer shell |
| $NI_{\Sigma}$ | Total magnetizing force |
| $P_{bl}$ | Transistor base loss |
| $P_{cl}$ | Transistor collector loss |
| $P_{cow}$ | Power loss in the core plus the end webbs |
| $P_{cow(50V)}$ | Core and webb loss at 50V supply |
| $P_{culpt}$ | Copper losses in the transformer primary |
| $P_{cults}$ | Copper losses in the transformer secondary |
| $P_{excul}$ | Excitation copper loss |
| $P_{exl}$ | Excitation loss |
| $P_{exl(40V)}$ | Excitation loss at 40V supply |
| $P_{exl(50V)}$ | Excitation loss at 50V supply |
| $P_{fexl}$ | Ferrite excitation loss |
| $P_{fl}$ | Power loss in ferrite |
| $P_g$ | Total air gap exciting power |

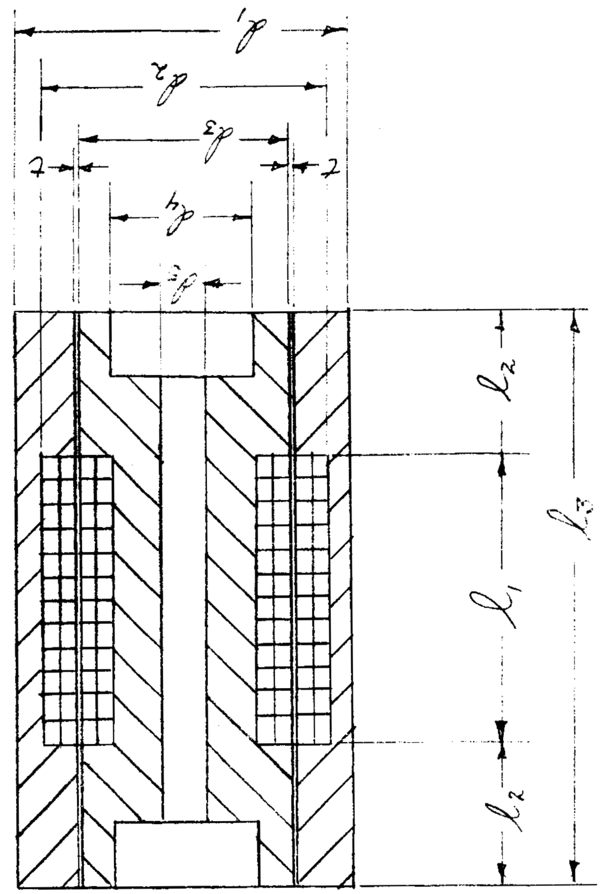
| | |
|---|---|
| $P_{gexl(40V)}$ | Air gap excitation loss at 40V supply |
| $P_{gexl(50V)}$ | Air gap excitation loss at 50V supply |
| $P_{pcul}$ | Primary copper loss |
| $P_{residual}$ | Loss constant for "Cermag" 24B in watts per cubic centimeter Hertz |
| $P_{scul}$ | Secondary copper loss |
| $P_{shl}$ | Power loss in transformer shell |
| $P_{sh(50V)}$ | Power losses in shell at 50V supply |
| $P_{\Sigma}$ | Total power |
| $P_{\Sigma cul(40V)}$ | Total copper loss at 40V supply |
| $P_{\Sigma cul(50V)}$ | Total copper loss at 50V supply |
| $P_{\Sigma ex(40V)}$ | Total excitation losses at 40V supply |
| $P_{\Sigma ex(50V)}$ | Total excitation losses at 50V supply |
| $P_{\Sigma fl(40V)}$ | Ferrite losses at 40V supply |
| $P_{\Sigma fl(50V)}$ | Total ferrite losses at 50V supply |
| $P_{\Sigma l}$ | Total losses |
| $P_{\Sigma l(40V)}$ | Total losses at 40V supply |
| $P_{\Sigma l(50V)}$ | Total losses at 50V supply |
| $P_{\Sigma ml}$ | Total active magnetizing losses |
| $P_{\Sigma Qdl}$ | Total driving power per pair of transistors |
| $P_{\Sigma Ql}$ | Total steady state transistor loss |
| $P_{\Sigma Ql(40V)}$ | Total transistor dissipation per pair at 40V DC supply |
| $P_{\Sigma Ql(50V)}$ | Total transistor dissipation per pair at 50V DC supply |
| $\varphi$ | Magnetic flux density |

| | |
|---|---|
| $\varphi_{co}$ | Peak magnetic flux density in the core |
| $\varphi_{sh}$ | Peak magnetic flux density in the transformer shell |
| Q | Transistor |
| $R_{bextr}$ | Transistor base external resistor |
| $R_o$ | Effective output load resistance |
| $R_p$ | Transformer primary winding resistance |
| $R_s$ | Transformer secondary resistance |
| S | Switch |
| $\Sigma l(40V)$ | Total losses with a 40V supply |
| $\Sigma l(50V)$ | Total losses with a 50V supply |
| $\Sigma_{lm}$ | Total magnetic losses |
| $\Sigma_{\varphi co}$ | Total magnetic flux in the transformer core |
| T | Transformer |
| tg | Length of the air gap |
| $\theta$ | Phase angle of exciting current with respect to the impressed voltage |
| $V_{1345}$ | Ferrite volume in $cm^3$ operating at $\varphi$ = 1345 Gauss |
| Vco | Ferrite core volume in $cm^3$ |
| $V_{cow(40V)}$ | Volume of core and webbs operating with 40V supply |
| $V_{cow(50V)}$ | Volume of core and webbs operating at 50V supply |
| $V_{sh(40V)}$ | Volume of shell operating at 40V supply |
| $V_{sh(50V)}$ | Volume of shell operating at 50V supply |



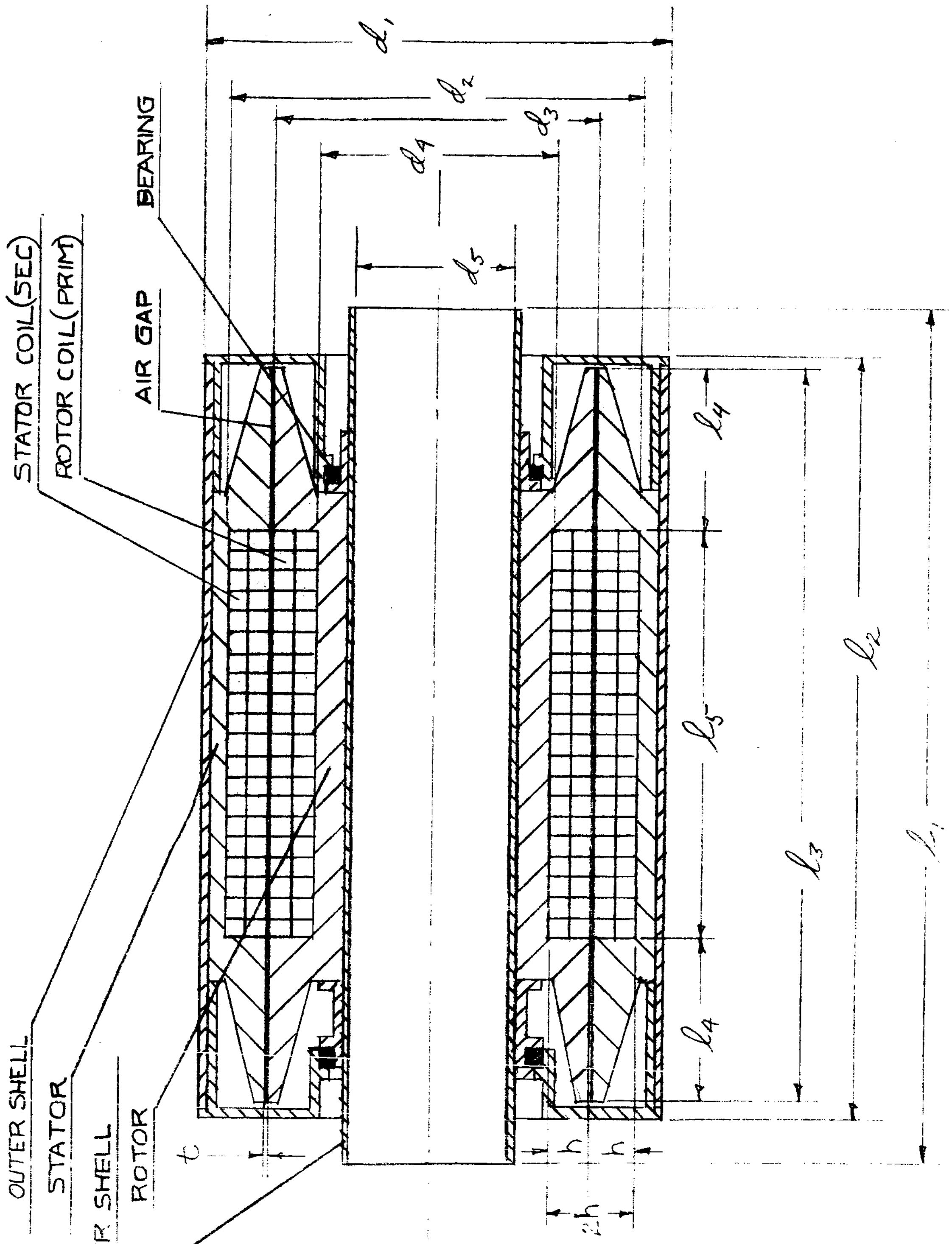

TEST TRANSFORMER

FIG-PD-1-



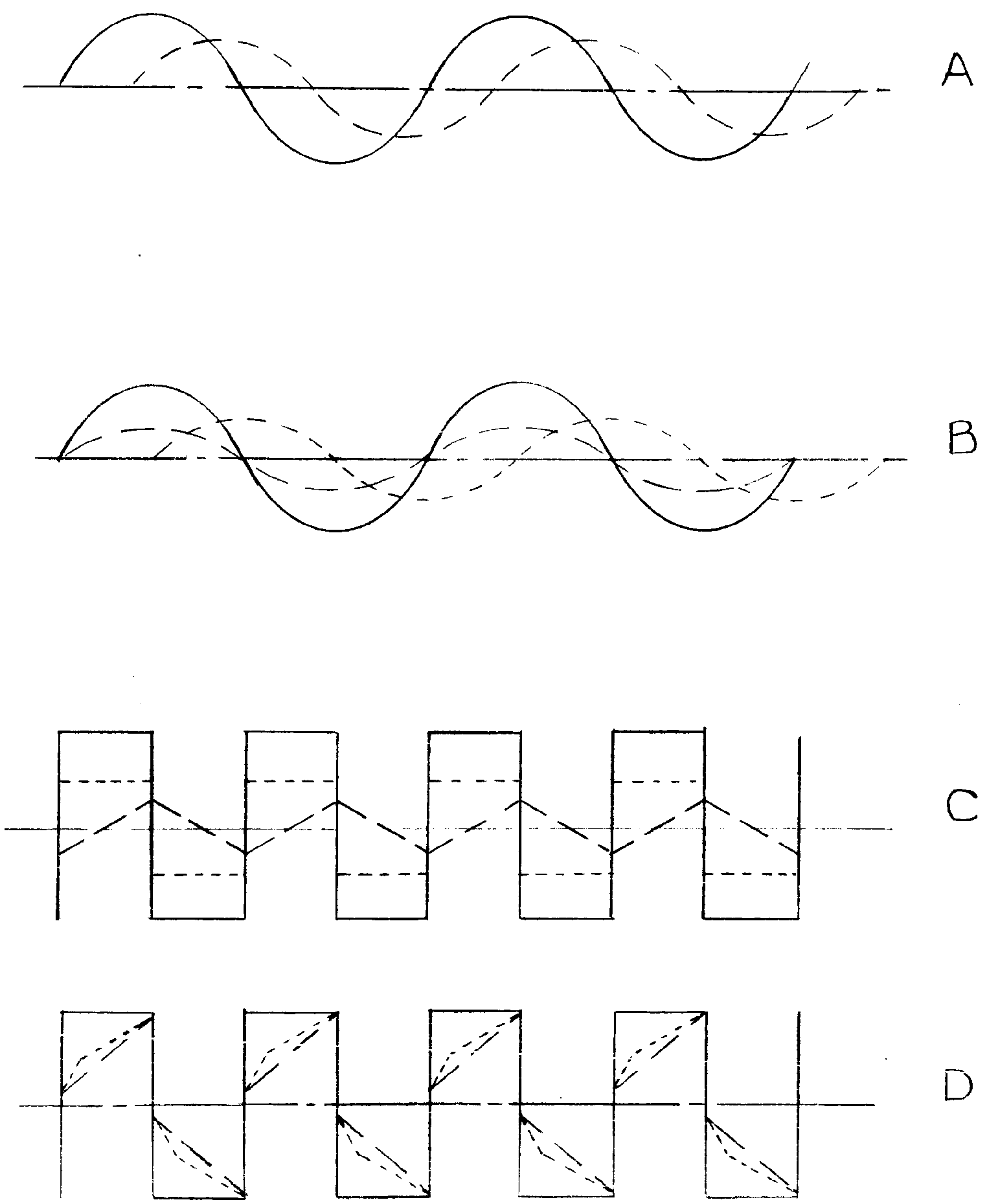
MATHEMATICAL MODEL

FIG-PD-2-



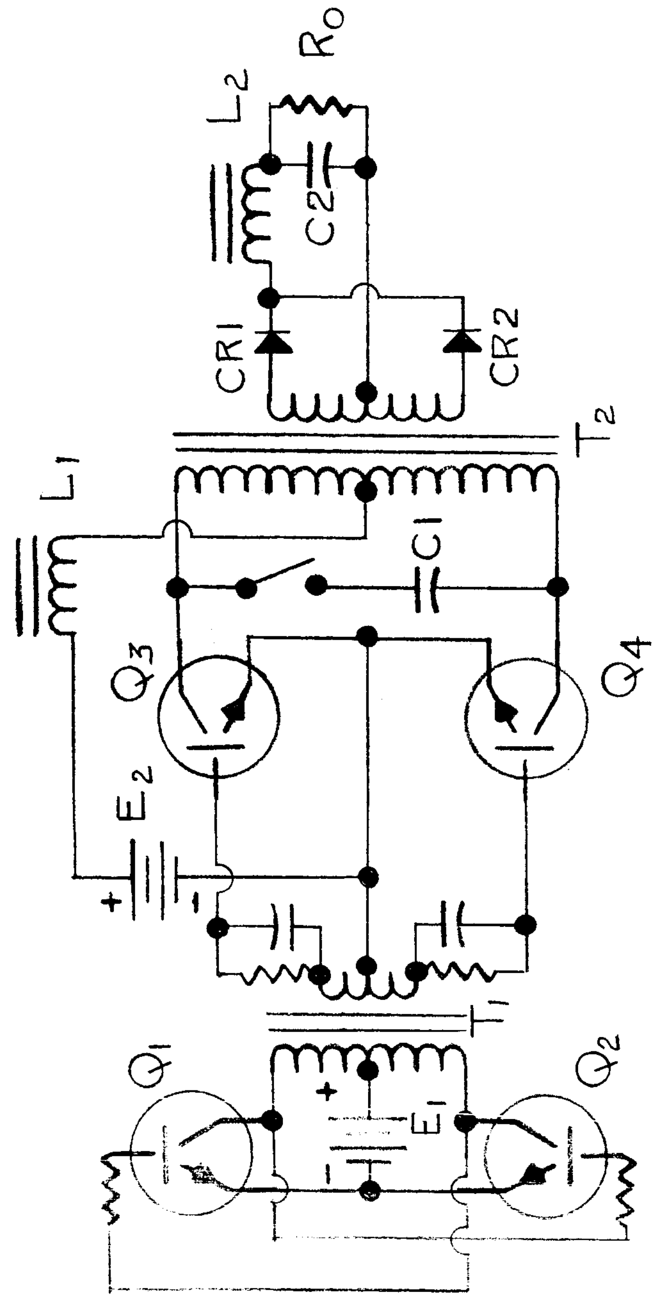

FINAL TEST DESIGN

Fig - PD - 3 -



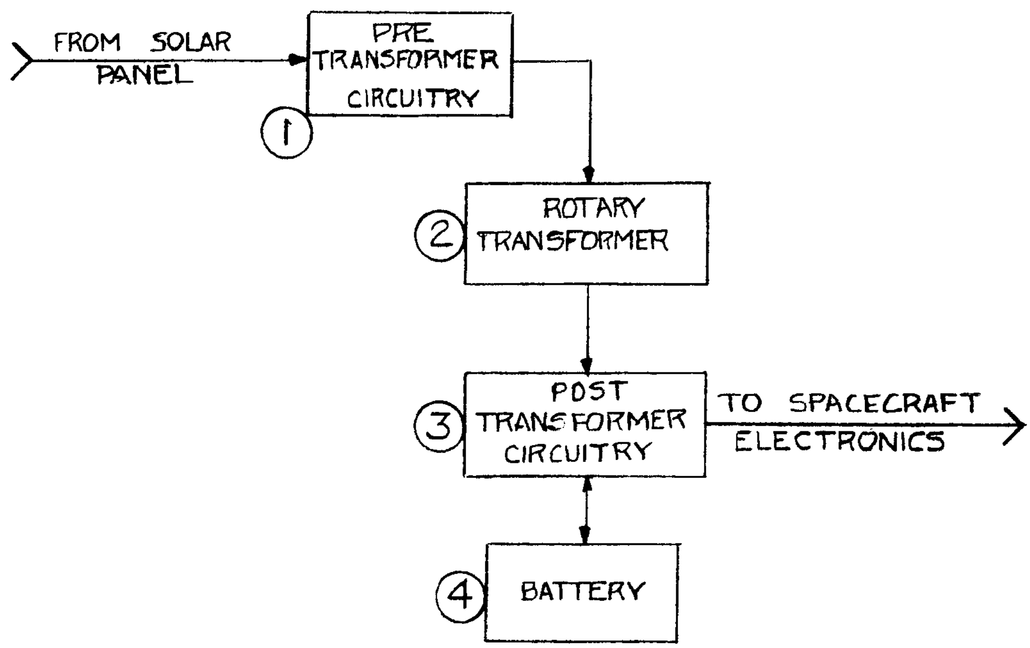

EXCITATION WAVE FORMS

FIG - PD -4 -



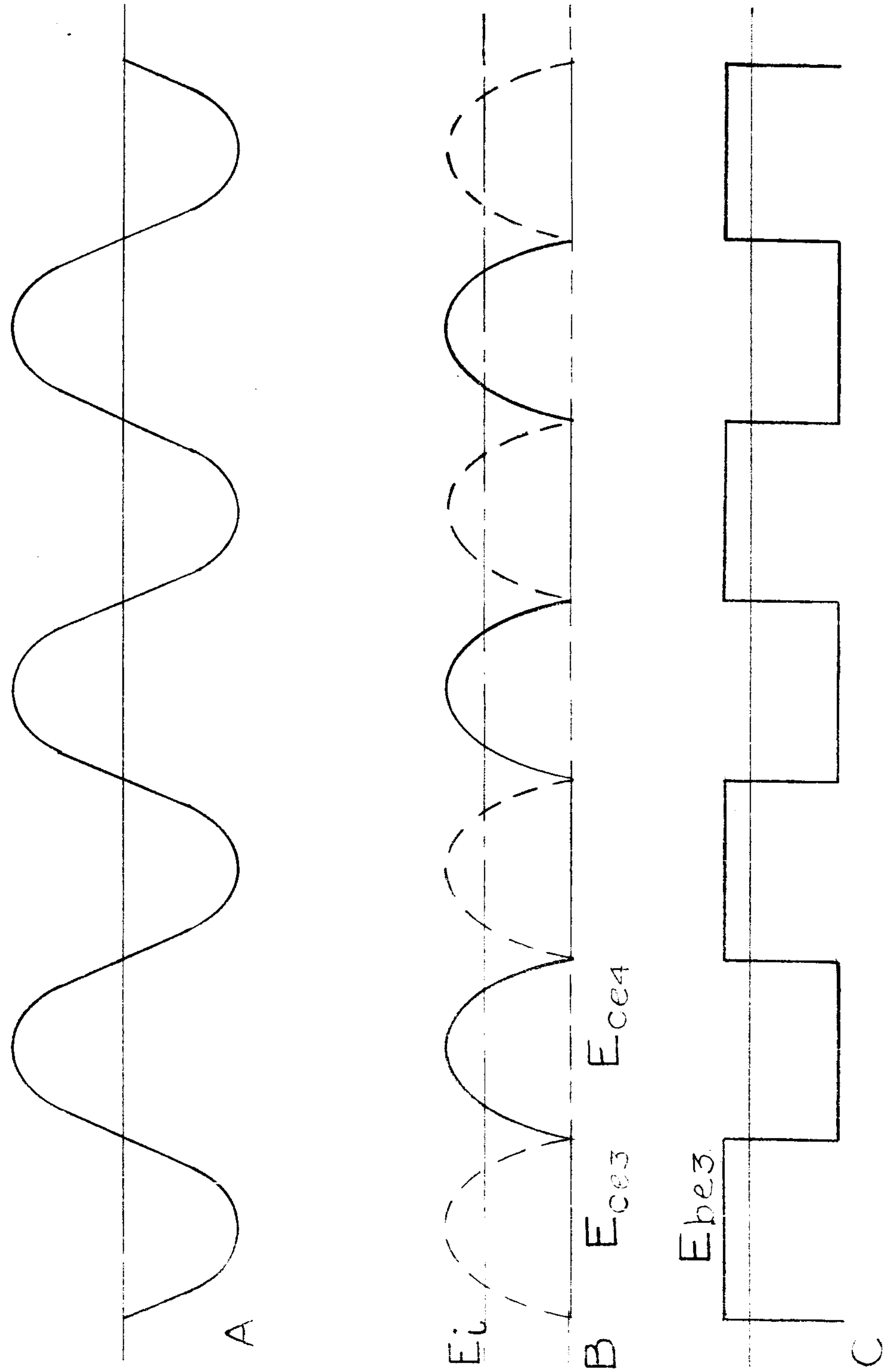

INVERTER CIRCUIT

FIG - PD - 5 -



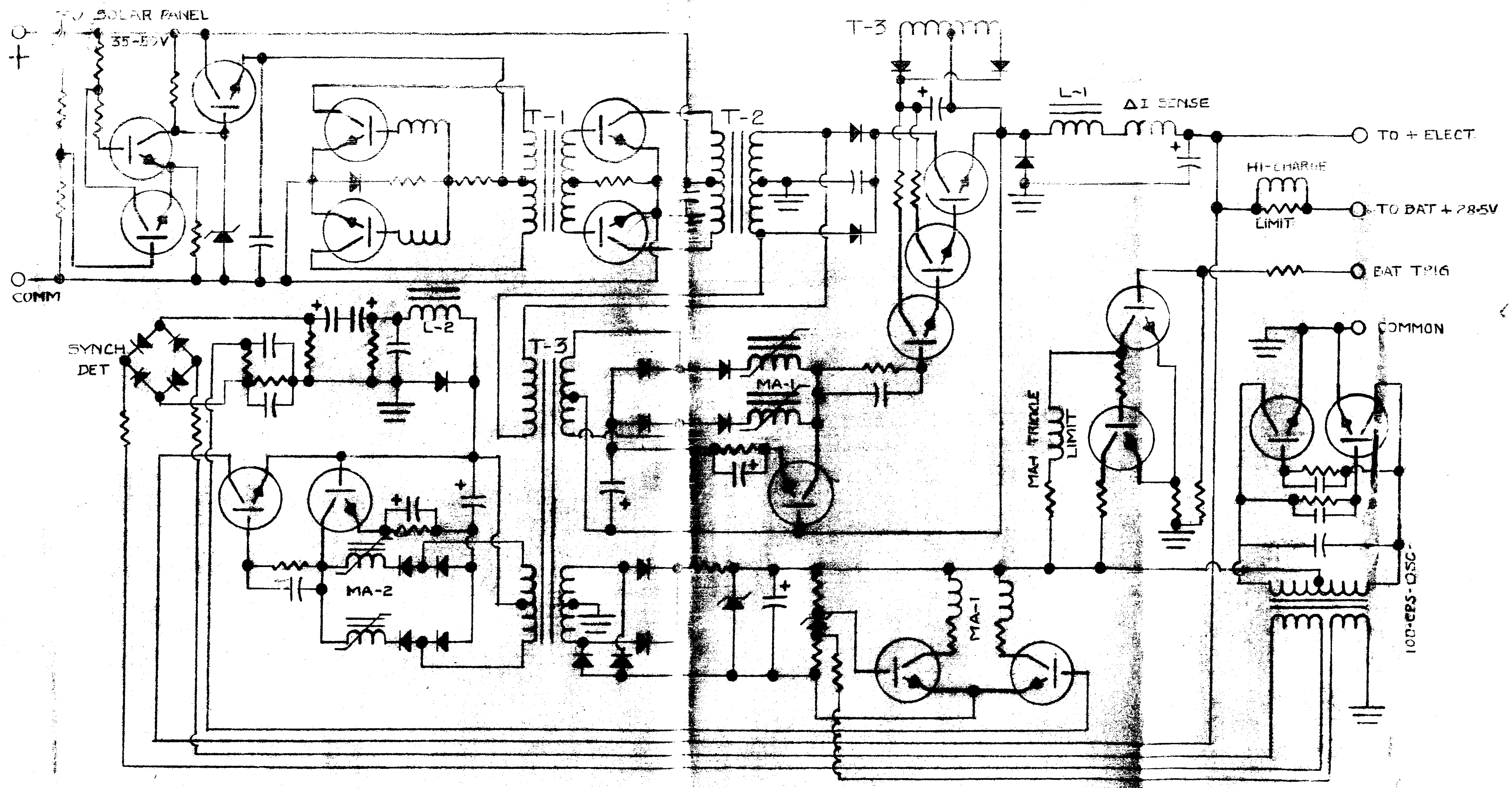

SYSTEM CIRCUIT GROUPING

FIG - P.D-6 -




INVERTER WAVE FORMS

FIG-PD-7-




SYSTEM SCHEMATIC

FIG - PD - 8 -